

Probing the coupling of heavy dark matter to nucleons by detecting neutrino signature from the Earth's core

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Abstract

We argue that the detection of neutrino signature from the Earth's core can effectively probe the coupling of heavy dark matter ($m_\chi > 10^4$ GeV) to nucleons. We first note that direct searches for dark matter (DM) in such a mass range provide much less stringent constraint than the constraint provided by such searches for $m_\chi \sim 100$ GeV. Furthermore the energies of neutrinos arising from DM annihilation inside the Sun cannot exceed a few TeVs at the Sun surface due to the attenuation effect. Therefore the sensitivity to the heavy DM coupling is lost. Finally, the detection of neutrino signature from galactic halo can only probe DM annihilation cross sections. We present neutrino event rates in IceCube and KM3NeT arising from the neutrino flux produced by annihilation of Earth-captured DM heavier than 10^4 GeV. The IceCube and KM3NeT sensitivities to spin independent DM-proton scattering cross section $\sigma_{\chi p}$ in this mass range are presented for both isospin symmetric and isospin violating cases.

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I. INTRODUCTION

Evidences for the dark matter (DM) are provided by many astrophysical observations, although the nature of DM is yet to be uncovered. The most popular candidates for DM are weak interacting massive particles (WIMP), which we shall assume in this work. DM can be detected either directly or indirectly with the former observing the nucleus recoil as DM interacts with the target nuclei in the detector and the latter detecting final state particles resulting from DM annihilation or decays. The direct detection is possible because that the dark matter particles constantly bombard the Earth as the Earth sweeps through the local halos. Sensitivities to $\sigma_{\chi p}$ from DM direct searches are low for large m_χ . Given a fixed DM mass density ρ_{DM} in the solar system, the number density of DM particles is inversely proportional to m_χ . Furthermore, the nuclear form factor suppression is more severe for DM-nucleus scattering for large m_χ . For a review of direct detection, see [1].

In this work, we propose to probe the coupling of heavy DM to nucleons by indirect approach with neutrinos. We note that the flux of DM induced neutrinos from galactic halo is only sensitive to $\langle\sigma v\rangle$. Furthermore, the energies of neutrinos from the Sun can not exceed a few TeVs due to severe energy attenuation during the propagation inside the Sun. Hence, for $m_\chi > 10^4$ GeV, we turn to the possibility of probing such DM with the search of neutrino signature from the Earth's core.

It is important to note that, for $E_\nu \gtrsim 100$ TeV, all flavors of neutrinos interact with nucleons inside the Earth with a total cross section $\sigma \propto E^{0.5}$ [2]. Charged-current (CC) and neutral-current (NC) neutrino-nucleon interactions occur in the ratio 0.71:0.29 and the resulting lepton carries about 75 % of the initial neutrino energy in both cases [2]. During CC interaction, initial ν_e and ν_μ will disappear and the resulting e and μ will be brought to rest due to their electromagnetic energy losses. Thus high-energy ν_e and ν_μ are absorbed by the Earth. However the situation is very different for ν_τ [3, 4], because except for very high energies ($\gtrsim 10^6$ TeV), the tau lepton decay length is less than its range, so that the tau lepton decays in flight without significant energy loss. In every branch of tau decays, ν_τ is produced. In this regeneration process $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$, the regenerated ν_τ carries about 1/3 of the initial ν_τ energy [5, 6]. Those ν_τ arriving at the detector site can be identified through shower events. We further note that 18% of the tau decays are $\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu$ and another 18% are $\tau \rightarrow \nu_\tau e \bar{\nu}_e$. These secondary anti-neutrinos ($\bar{\nu}_e, \bar{\nu}_\mu$) carry roughly 1/6 of the initial

ν_τ energy. The secondary $\bar{\nu}_\mu$ flux is detectable as muon track events or hadronic shower events. Similarly, the secondary $\bar{\nu}_e$ flux is also detectable as shower events [7]. In summary, as tau neutrinos propagate through the Earth, the regenerated tau neutrinos by prompt tau decays can produce relatively large fluxes of secondary $\bar{\nu}_e$ and $\bar{\nu}_\mu$ and hence greatly enhance the detectability of the initial ν_τ . Therefore we study the neutrino signature from DM annihilation channels $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ from the Earth's core.

The status of IceCube search for neutrinos coming from DM annihilation in the Earth's core has been reported [8]. The earlier IceCube data on the search for astrophysical muon neutrinos was used to constrain the cross section of DM annihilation $\chi\chi \rightarrow \nu\bar{\nu}$ in the Earth's core [9] for m_χ in the favored range of PAMELA and Fermi experiments [10, 11]. The sensitivity of IceCube-DeepCore detector to various DM annihilation channels in the Earth's core for low mass DM has also been studied in Ref. [12]. In this work, we shall extend such an analysis for $m_\chi > 10^4$ GeV as mentioned before. We consider both muon track events and cascade events induced by neutrinos in IceCube observatory. The DM annihilation channels $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ will be analyzed. Besides analyzing these signature in IceCube, we also study the sensitivity of KM3NeT observatory to the same signature. The KM3NeT Observatory [13] is a multi-cubic-kilometer scale deep sea neutrino telescope to be built in the Mediterranean Sea. KM3NeT will act as IceCube's counterpart on the Northern hemisphere. Because of its several cubic kilometers instrumental volume, KM3NeT will be the largest and most sensitive high energy neutrino detector. The sensitivities to DM annihilation cross section $\langle\sigma v\rangle$ and DM-proton scattering cross section $\sigma_{\chi p}$ are expected to be enhanced significantly by KM3NeT.

This paper is organized as follows. In Sec. II, we discuss DM capture and annihilation rates inside the Earth and the resulting neutrino flux. We note that the neutrino flux in this case depend on both DM annihilation cross section $\langle\sigma v\rangle$ and DM-proton scattering cross section $\sigma_{\chi p}$. In Sec. III, we discuss the track and shower event rates resulting from DM annihilation in the Earth core. The background event rates from atmospheric neutrino flux are also calculated. In Section IV, we compare signature and background event rates and obtain sensitivities of neutrino telescopes to DM-proton scattering cross section. We present those sensitivities in both isospin symmetric and isospin violating [14, 15] cases, respectively. We present the summary and conclusion in Section V.

II. DARK MATTER ANNIHILATION IN THE EARTH CORE

A. DM capture and annihilation rates in the Earth core

The neutrino differential flux Φ_{ν_i} from $\chi\chi \rightarrow f\bar{f}$ can be expressed as

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = P_{\nu,\text{surv}}(E_\nu) \frac{\Gamma_A}{4\pi R_\oplus^2} \sum_f B_f \left(\frac{dN_{\nu_i}}{dE_{\nu_i}} \right)_f \quad (1)$$

where R_\oplus is the Earth radius, $P_{\nu,\text{surv}}$ is the neutrino survival probability from the source to the detector, B_f is the branching ratio of the annihilation channel $\chi\chi \rightarrow f\bar{f}$, dN_{ν_i}/dE_{ν_i} is the energy spectrum of ν_i produced per DM annihilation in the Earth's core, and Γ_A is the DM annihilation rate in the Earth. To compute dN_{ν_i}/dE_{ν_i} , we employed `WimpSim` [16] with a total of 50,000 Monte-Carlo generated events.

The annihilation rate, Γ_A , can be obtained by solving the DM evolution equation in the Earth core [17, 18],

$$\dot{N} = C_C - C_A N^2 - C_E N \quad (2)$$

where N is the DM number density in the Earth core, C_C is the capture rate, and C_E is the evaporation rate. The evaporation rate is only relevant when $m_\chi \lesssim 5$ GeV [19–21] while a more refined calculation found typically $m_\chi \lesssim 3.3$ GeV [22], which are much lower than our interested mass scale. Thus C_E can be ignored in this work. The detail discussion and derivation to the evolution equation Eq. (2) can be found in Ref. [19–23]. Solving Eq. (2) thus gives the annihilation rate

$$\Gamma_A = \frac{C_C}{2} \tanh^2 \left(\frac{t}{\tau_\oplus} \right), \quad (3)$$

where τ_\oplus is the time scale when the DM capture and annihilation in the Earth core reaches the equilibrium state. Taking $t \approx 10^{17}$ s the lifetime of the solar system, we have

$$\frac{t}{\tau_\oplus} \approx 1.9 \times 10^4 \left(\frac{C_C}{\text{s}^{-1}} \right)^{1/2} \left(\frac{\langle \sigma v \rangle}{\text{cm}^3 \text{s}^{-1}} \right)^{1/2} \left(\frac{m_\chi}{10 \text{ GeV}} \right)^{3/4}, \quad (4)$$

where $\langle \sigma v \rangle$ is the DM annihilation cross section, m_χ is the DM mass, and C_C is the DM capture rate which can be expressed as [23]

$$C_C \propto \left(\frac{\rho_0}{0.3 \text{ GeV cm}^{-3}} \right) \left(\frac{270 \text{ km s}^{-1}}{\bar{v}} \right) \left(\frac{\text{GeV}}{m_\chi} \right) \left(\frac{\sigma_{\chi p}^0}{\text{pb}} \right) \sum_i F_{A_i}(m_\chi), \quad (5)$$

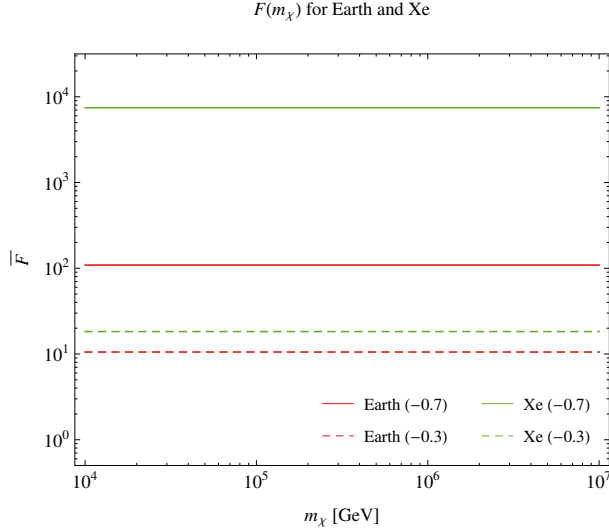


FIG. 1. Isospin violation effect for different targets. For xenon target, \bar{F} reduces to F_Z . In this case, F_Z is as large as 10^4 for $f_n/f_p = -0.7$. With the Earth as the target, $\bar{F} \equiv \sum_Z f_Z F_Z$ with f_Z the fraction of proton targets originating from chemical elements with the atomic number Z .

where ρ_0 is the local DM density, \bar{v} is the DM velocity dispersion, $\sigma_{\chi p}^0$ is the DM-nucleon cross section by assuming isospin conservation and $F_{A_i}(m_\chi)$ is the product of various factors for element A_i including the mass fraction, chemical element distribution, kinematic suppression, form-factor and reduced mass.

B. Isospin violation effects to bounds set by direct and indirect searches

Recent studies [14, 15, 24, 25] suggested that DM-nucleon interactions do not necessarily respect the isospin symmetry. It has been shown that [15, 25, 26] isospin violation can dramatically change the bound on $\sigma_{\chi p}$ from the current direct search. Therefore isospin violation effect is also taken into consideration in our analysis.

Given an isotope with atomic number Z , atom number A_i , and the reduced mass $\mu_{A_i} \equiv m_\chi m_{A_i} / (m_\chi + m_{A_i})$ for the isotope and the DM particle, the usual DM-nucleus cross section with the approximation $m_p \approx m_n$ can be written as [23]

$$\sigma_{\chi A_i} = \frac{4\mu_{A_i}^2}{\pi} [Zf_p + (A_i - Z)f_n]^2 = \frac{\mu_{A_i}^2}{\mu_p^2} \left[Z + (A_i - Z) \frac{f_n}{f_p} \right]^2 \sigma_{\chi p} \quad (6)$$

where f_p and f_n are the effective couplings of DM to protons and neutrons, respectively. Thus, following Ref. [26], it is convenient to define the ratio between $\sigma_{\chi p}$ and $\sigma_{\chi p}^0$ where the

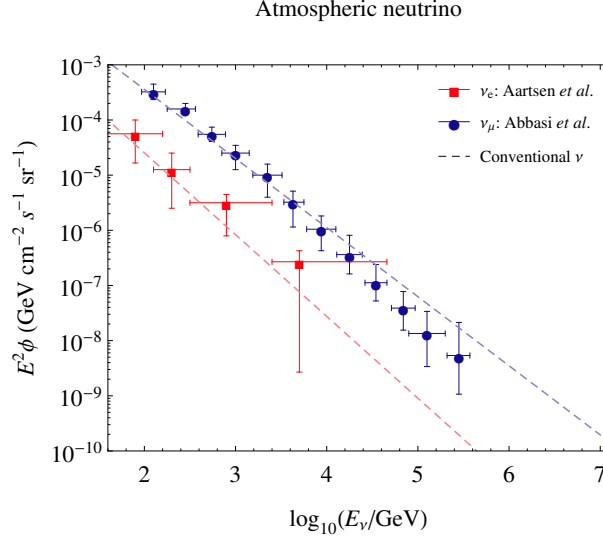


FIG. 2. The atmospheric ν_e and ν_μ flux.

former is the derived bound on DM-proton cross section with isospin violation while the latter is the derived bound for isospin symmetric case. For a particular species of chemical element with atomic number Z , we have

$$\frac{\sigma_{\chi p}}{\sigma_{\chi p}^0} = \frac{\sum_i \eta_i \mu_{A_i}^2 A_i^2}{\sum_i \eta_i \mu_{A_i}^2 [Z + (A_i - Z) f_n / f_p]^2} \equiv F_Z \quad (7)$$

where η_i is the percentage of the isotope A_i . We note that for a target containing multiple species of chemical elements, the factor F_Z should be modified into $\bar{F} \equiv \sum_Z f_Z F_Z$, where f_Z is the fraction of proton targets originating from elements with the atomic number Z . Fig. 1 shows the numerical values of \bar{F} for different m_χ when $f_n/f_p \neq 1$. Since m_χ is taken to be larger than 10^4 GeV, \bar{F} is insensitive to m_χ .

III. DM SIGNAL AND ATMOSPHERIC BACKGROUND EVENTS

The neutrino event rate in the detector resulting from DM annihilation in Earth's core is

$$N_\nu = \int_{E_{\text{th}}}^{m_\chi} \frac{d\Phi_\nu}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega \quad (8)$$

where E_{th} is the detector threshold energy, $d\Phi_\nu/dE_\nu$ is the neutrino flux from DM annihilation, A_ν is the contained detector effective area and Ω is the solid radian. The neutrino oscillation is strongly suppressed when neutrino carries energy beyond tens of GeV. Thus the only significant effect to our interested DM mass region is neutrino attenuation during the

propagation from the production point to the detector. The attenuation effect is included in the survival probability, $P_{\nu,\text{surv}}(E_\nu)$, in Eq. (1).

After arriving at the detector, neutrinos are able to produce track or cascade events through neutral current (N.C.) or charge current (C.C.) interactions with the medium enclosed by the detector. In this work, we consider track and cascade events both inside the detector like IceCube. To compute the event rates in IceCube, the contained effective areas A_ν for different neutrino flavors in Eq. (8) can be estimated from the effective volume, V_{eff} , in Ref. [27] by the following relation:

$$A_\nu(E_\nu) = V_{\text{eff}} \frac{N_A}{M_{\text{ice}}} (n_p \sigma_{\nu p}(E_\nu) + n_n \sigma_{\nu n}(E_\nu)) \quad (9)$$

where N_A is the Avogadro constant, M_{ice} is the molar mass of ice, $n_{p,n}$ is the number density of proton/neutron per mole of ice and $\sigma_{\nu p,n}$ is the neutrino-proton/neutron cross section. Simply swaps the sign $\nu \rightarrow \bar{\nu}$ for anti-neutrino.

We note that another neutrino telescope KM3NeT located in the norther-hemisphere is also capable to detect the neutrino signal from DM annihilation in the Earth. In the present stage, KM3NeT has ν_μ C.C. effective area published [28]. Therefore we consider only track events in KM3NeT.

The atmospheric background event rate is similar to Eq. (8), by replacing $d\Phi_\nu/dE_\nu$ with atmospheric neutrino flux,

$$N_{\text{atm}} = \int_{E_{\text{th}}}^{E_{\text{max}}} \frac{d\Phi_\nu^{\text{atm}}}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega. \quad (10)$$

To facilitate our calculation, the atmospheric neutrino flux $d\Phi_\nu^{\text{atm}}/dE_\nu$ shown in Fig. 2 is taken from Refs. [29, 30] and extrapolated to $E_\nu \simeq 10^7$ GeV. We set $E_{\text{max}} = m_\chi$ in order to compare with the DM signal.

IV. RESULTS

We present the sensitivity as a 2σ detection significance in 5 years, calculated with the convention,

$$\frac{s}{\sqrt{s+b}} = 2.0 \quad (11)$$

where s is the DM signal, b is the atmospheric background, and 2.0 refers to the 2σ detection significance. The atmospheric ν_τ flux is extremely small and can be ignored in our analysis.

Thus we take ν_e and ν_μ as our major background sources. The detector threshold energy E_{th} in Eqs. (8) and (10) is set to be 10^4 GeV in order to suppress the background events. In the following two subsections, we present two isospin scenarios for the constraints on $\langle\sigma v\rangle$ and $\sigma_{\chi p}$. One is $f_n/f_p = 1$, the isospin symmetry case, and the other is $f_n/f_p = -0.7$, the isospin violation one. Isospin violation scenario is often used to alleviate the inconsistency between the results of different DM direct detection experiments for low m_χ . $f_n/f_p = -0.7$ is the value for which the $\sigma_{\chi p}^{\text{SI}}$ sensitivity of a xenon detector is maximally suppressed by isospin violation. Although our study focus on heavy DM accumulated inside the Earth and xenon is very rare among the constituent elements of the Earth, we shall see that $f_n/f_p \sim -0.7$ leads to most optimistic IceCube sensitivities on both $\langle\sigma v\rangle$ and $\sigma_{\chi p}^{\text{SI}}$. In the next subsection, we present various f_n/f_p values and their impacts to the IceCube sensitivities to the annihilation channel $\chi\chi \rightarrow \tau^+\tau^-$.

To derive sensitivities to DM-annihilation cross section $\langle\sigma v\rangle$, we make use of the $\sigma_{\chi p}$ from the extrapolation of the LUX bound [31] to $m_\chi > 10$ TeV. We find that the total rate R measured by the direct search is given by $R \propto \sigma_{\chi p}\rho_0/m_\chi m_{A_i}$ for $m_\chi \gg m_{A_i}$ [23] with ρ_0 the local DM density and m_{A_i} the mass of the target with i the index for isotopes. Thus $\sigma_{\chi p} \propto m_\chi m_{A_i} R/\rho_0$ and it is reasonable to extrapolate LUX bound linearly in the mass scale when $m_\chi > 10$ TeV.

A. IceCube sensitivities

In Fig. 3 we present the IceCube sensitivities to $\langle\sigma v\rangle$ of $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels in the Earth core with both track and cascade events. For the $\chi\chi \rightarrow \nu\bar{\nu}$ production mode, we assume equal-flavor distribution (1/3 for each flavor). In the left panel where $f_n = f_p$, the IceCube sensitivities to $\chi\chi \rightarrow \tau^+\tau^-$ and $\chi\chi \rightarrow W^+W^-$ annihilation channels with track events are only available in a narrow DM mass range. For most of the DM mass range considered here, the estimated sensitivities are either disfavored by the CMB constraint or reach into the equilibrium region where the 2σ sensitivity cannot be achieved. The raising tails for all sensitivities are due to the neutrino attenuation in the high energy such that larger $\langle\sigma v\rangle$ is required to generate sufficient number of events.

For $m_\chi \gtrsim 10^6$ GeV, it is seen that IceCube is more sensitive to $\chi\chi \rightarrow \tau^+\tau^-$ than to $\chi\chi \rightarrow \nu\bar{\nu}$ for cascade events. This can be understood by the fact that the neutrino spectrum

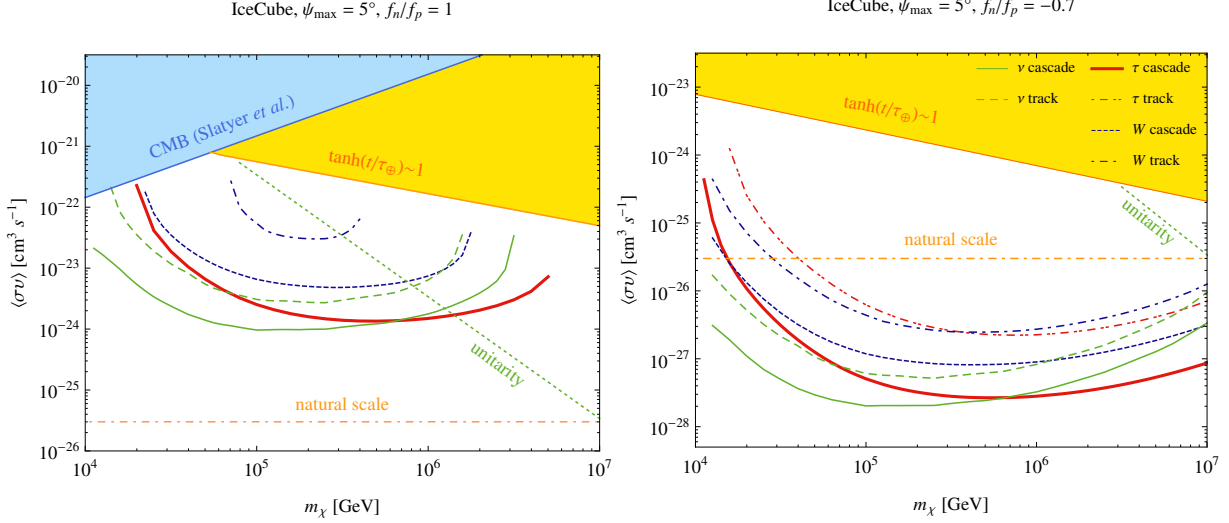


FIG. 3. The IceCube 5-year sensitivity at 2σ to $\langle\sigma v\rangle$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels with track and cascade events with $\psi_{\max} = 5^\circ$. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The yellow-shaded region is the parameter space for the equilibrium state and the blue-shaded region is the constraint from CMB [49].

from $\chi\chi \rightarrow \nu\bar{\nu}$ is almost like a spike near m_χ . As m_χ becomes larger, neutrinos produced by the annihilation are subject to more severe energy attenuation. On the other hand, the neutrino spectrum from $\chi\chi \rightarrow \tau^+\tau^-$ is relatively flat in the whole energy range. The energy attenuation only affects the higher energy neutrinos.

In the isospin violation scenario, the ratio $f_n/f_p = -0.7$ could weaken the LUX bound by four orders of magnitude, i.e., the LUX upper bound on $\sigma_{\chi p}$ is raised by four orders of magnitude. Taking a four orders of magnitude enhanced $\sigma_{\chi p}$, the DM capture rate is enhanced by two orders of magnitude since the suppression factor due to isospin violation is around 10^{-2} for chemical elements in the Earth's core. With the DM capture rate enhanced by two orders of magnitude, the IceCube sensitivities to $\langle\sigma v\rangle$ of various annihilation channels can be improved by about four orders of magnitude by simple scaling observed in Refs. [9, 12]. Therefore, the sensitivities could reach below the natural scale $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1}$.

For DM annihilation, a general upper bound on $\langle\sigma v\rangle$ is set by unitarity condition [32–34]. The DM annihilation cross section is assumed to be s -wave dominated in the low-velocity

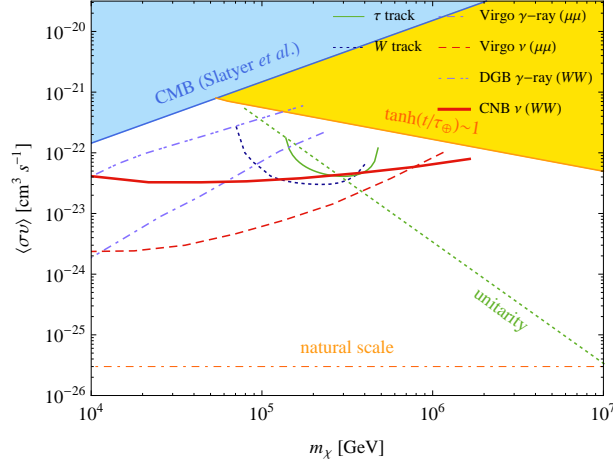


FIG. 4. The IceCube 5-year sensitivity at 2σ to $\langle\sigma v\rangle$ for $\chi\chi \rightarrow W^+W^-$ and $\tau^+\tau^-$ annihilation channels for track events with $\psi_{\max} = 5^\circ$, respectively. The dot-dashed line is the gamma-ray constraint on the $\chi\chi \rightarrow \mu^+\mu^-$ annihilation cross section in Virgo cluster [38]. The dashed line is the projected full IceCube 2σ sensitivity in 5 years to $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ in Virgo cluster in the presence of substructures with track events [38]. The dot-dot-dashed line is the cascade gamma-ray constraint on $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ from diffuse gamma-ray background (DGB) [35]. The thick solid line is the full IceCube sensitivity in 3 years to $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ from cosmic neutrino background (CNB) with track events [35].

limit. Hence it can be shown that [32]

$$\langle\sigma v\rangle \leq \frac{4\pi}{m_\chi^2 v} \simeq 1.5 \times 10^{-13} \frac{\text{cm}^3}{\text{s}} \left(\frac{\text{GeV}}{m_\chi} \right)^2 \left(\frac{300 \text{ km/s}}{v_{\text{rms}}} \right). \quad (12)$$

This unitarity bound with $v_{\text{rms}} \simeq 13 \text{ km s}^{-1}$ (escape velocity from the Earth) is also shown in Fig. 3. The unitarity bound can be evaded for non-point-like DM particles [33–35].

Galaxy clusters (GCs) are the largest gravitationally bound objects in the universe and their masses can be as large as 10^{15} times that of the Sun's ($10^{15} M_\odot$) [36, 37]. Many galaxies (typically $\sim 50 - 1000$) collect into GCs, but their masses consist of mainly dark matter. Thus GCs are the largest DM reservoirs in the universe and can be the ideal sources to look for DM annihilation signatures. With DM particles assumed to annihilate into $\mu^+\mu^-$ pairs, the predicted full IceCube 2σ sensitivity in 5 years to $\langle\sigma v\rangle$ for Virgo cluster in the presence of substructures with track events is derived in Ref. [38]. We present this sensitivity in Fig. 4 and we can see that it is better than our expected IceCube 5-year sensitivity at 2σ to

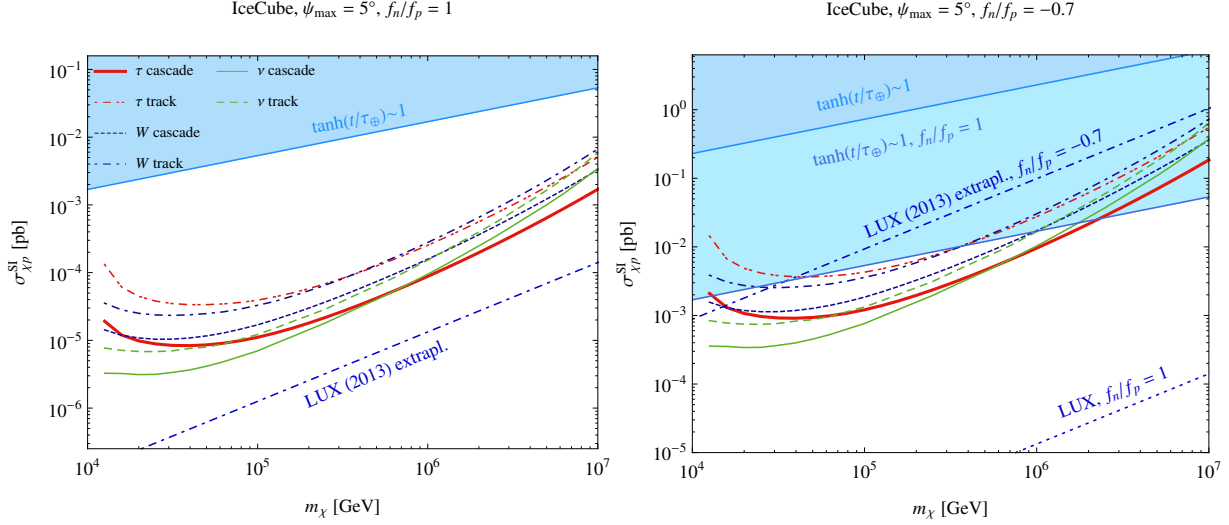


FIG. 5. The IceCube 2σ sensitivities in 5 years to $\sigma_{\chi p}^{\text{SI}}$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels with both track and cascade events with $\psi_{\text{max}} = 5^\circ$. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right. The blue-shaded region is the parameter space for the equilibrium state and the light-blue-shaded region on the right panel refers to the equilibrium-state parameter space for the isospin symmetry case as a comparison. An extrapolation of current LUX limit has been shown on the figures.

$\langle\sigma(\chi\chi \rightarrow \tau^+\tau^-)v\rangle$ with ν_μ track events. One of the reasons is because only 18% of τ decay to ν_μ . However, if we consider isospin violation scenario, our expected IceCube sensitivity with $f_n/f_p = -0.7$ will be much better than that for Virgo cluster. Except for neutrinos, DM annihilation in GCs can also produce a high luminosity in gamma rays. In Ref. [38], the authors also estimate gamma-ray constraints taking into account electromagnetic cascades caused by pair production on the cosmic photon backgrounds, from the flux upper limits derived by Fermi-LAT observations of GCs [39, 40]. We show in Fig. 4 the gamma-ray constraint on the $\chi\chi \rightarrow \mu^+\mu^-$ annihilation cross section for Virgo cluster taken from Ref. [38]. We can see that this constraint is weaker than our expected IceCube 5-year sensitivity at 2σ to $\langle\sigma(\chi\chi \rightarrow \tau^+\tau^-)v\rangle$ for $m_\chi \gtrsim 10^5$ GeV.

The diffuse gamma-ray background (DGB) was measured by Fermi Large Area Telescope (Fermi-LAT) above 200 MeV in 2010 [41]. Radio-loud active galactic nuclei (AGN) including blazars [42], star-forming and star-burst galaxies [43, 44], and heavy DM are the possible sources. In Ref. [35], the authors derive cascade gamma-ray constraints on the annihilation

cross section of heavy DM by requiring the calculated cascade gamma-ray flux not exceeding the measured DGB data at any individual energy bin by more than a given significance [45, 46]. We present the cascade gamma-ray constraint on $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ for DGB taken from Ref. [35] in Fig. 4. We note that this constraint is weaker than our predicted IceCube 5-year sensitivity at 2σ to $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$. On the other hand, for demonstrating the power of neutrino observations, we also show in Fig. 4 the predicted full IceCube sensitivity in 3 years to $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ for cosmic neutrino background (CNB) with track events taken from Ref. [35]. It is slightly less sensitive compared to our expected IceCube 5-year sensitivity at 2σ to $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ at $\sim 10^5$ GeV, while both sensitivities do not reach to the unitarity bound for $m_\chi \gtrsim 3 \times 10^5$ GeV.

Fig. 5 shows the IceCube sensitivities to spin-independent cross section $\sigma_{\chi p}^{\text{SI}}$ by analyzing track and cascade events from $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels in the Earth core. The threshold energy E_{th} is the same as before and we take $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1}$ as our input. Precisely speaking, the sensitivity to $\chi\chi \rightarrow \nu\bar{\nu}$ channel is the highest when $m_\chi \lesssim 10^6$ GeV and $\chi\chi \rightarrow \tau^+\tau^-$ after. However, the sensitivities to different channels can be taken as comparable since the differences between them are not significant.

When isospin is a good symmetry, the IceCube sensitivity is not as good as the constraint from the LUX extrapolation. However, with $f_n/f_p = -0.7$, the capture rate is reduced to 1% of the isospin symmetric value. Therefore one requires 100 times larger $\sigma_{\chi p}^{\text{SI}}$ to reach the same detection significance. However, the ratio $f_n/f_p = -0.7$ makes a more dramatic impact to the DM direct search using xenon as the target. The DM scattering cross section with xenon is reduced by four orders of magnitude. Hence the indirect search by IceCube could provide better constraint on $\sigma_{\chi p}^{\text{SI}}$ than the direct search in such a case.

B. KM3NeT sensitivities

Besides IceCube, the neutrino telescope KM3NeT located in the northern-hemisphere can also reach to a promising sensitivity in the near future [48]. Therefore it is worthwhile to comment on the performance of KM3NeT. Since KM3NeT only published ν_μ charge-current effective area in the present stage, we shall only analyze track events.

The results are shown in Fig. 6 and 7 with parameters chosen to be the same as those for computing the IceCube sensitivities. The sensitivities of KM3NeT are almost an order of

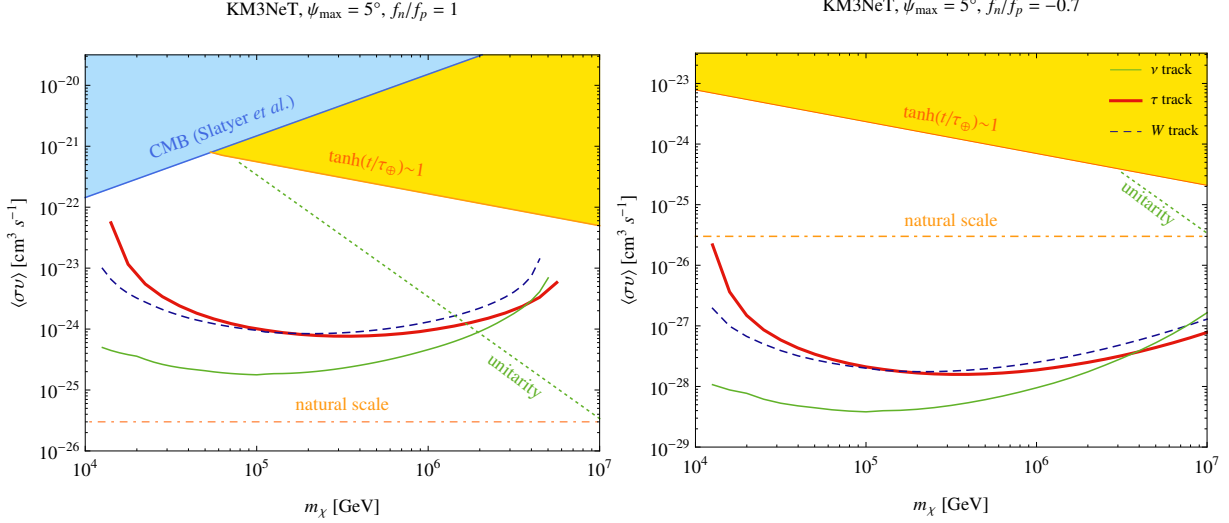


FIG. 6. The KM3NeT 2σ sensitivities in 5 years to $\langle\sigma v\rangle$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels with track events only and $\psi_{\max} = 5^\circ$. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The yellow-shaded region is the parameter space for the equilibrium state and the blue-shaded region is the constraint from CMB [49].

magnitude better than those of IceCube, since its ν_μ charge-current effective area is about one order of magnitude larger than that of IceCube.

C. Sensitivities with different f_n to f_p ratios

In the previous subsections, we have presented IceCube and KM3NeT sensitivities to $\langle\sigma v\rangle$ and $\sigma_{\chi p}^{\text{SI}}$ for $f_n/f_p = 1$ and -0.7 . To be thorough, it is worth discussing the effect to DM search with various f_n/f_p values. For simplicity, we shall focus on the $\chi\chi \rightarrow \tau^+\tau^-$ cascade events in IceCube.

In the left panel of Fig. 8, we present IceCube sensitivities to $\langle\sigma v\rangle$ with $f_n/f_p \in [-0.8, 1]$. We take the re-derived $\sigma_{\chi p}^{\text{SI}}$ from LUX using Eq. (7) which quantifies the isospin violation effect. Isospin violation not only leads to the suppression of DM capture rate by the Earth but also weakens the $\sigma_{\chi p}^{\text{SI}}$ bound from LUX. The overall effect is beneficial to the DM indirect search for f_n/f_p in a certain range. As shown in Fig. 8, the IceCube sensitivity to $\langle\sigma v\rangle$ improves as $f_n/f_p \rightarrow -0.7$ from the above. However, when f_n/f_p is smaller than -0.7 , the sensitivity to $\langle\sigma v\rangle$ becomes even worse than that in the isospin symmetry case.

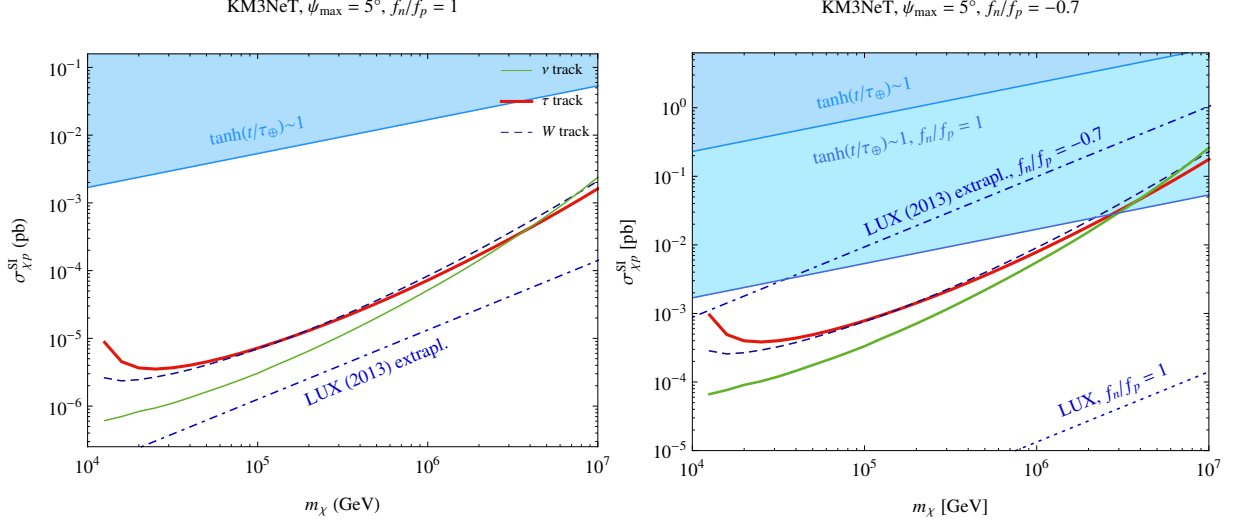


FIG. 7. The KM3NeT 2σ sensitivities in 5 years to $\sigma_{\chi p}^{\text{SI}}$ for $\chi\chi \rightarrow \tau^+\tau^-$, W^+W^- , and $\nu\bar{\nu}$ annihilation channels for track events only with $\psi_{\text{max}} = 5^\circ$. The isospin symmetry case, $f_n/f_p = 1$, is presented on the left panel, and the isospin violation case, $f_n/f_p = -0.7$, is presented on the right panel. The blue-shaded region is the parameter space for the equilibrium state and the light-blue-shaded region on the right panel refers to the equilibrium-state parameter space in the isospin symmetry case.

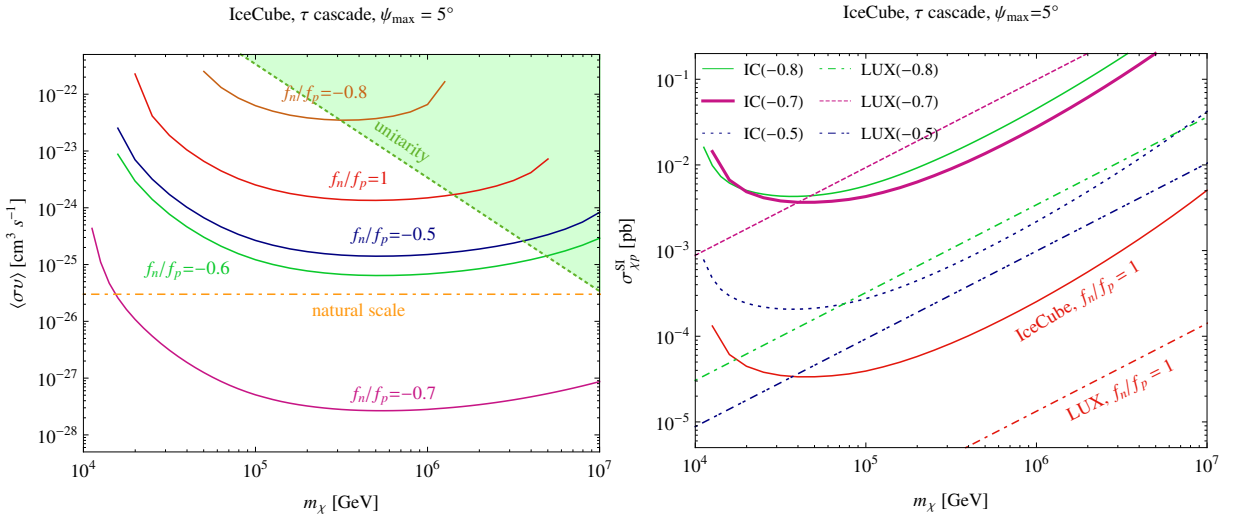


FIG. 8. The IceCube 5-year sensitivity at 2σ to $\langle\sigma v\rangle$ on the left panel and $\sigma_{\chi p}^{\text{SI}}$ on the right panel for $\chi\chi \rightarrow \tau^+\tau^-$ annihilation channels with cascade events for different degrees of isospin violation. We take the re-derived $\sigma_{\chi p}^{\text{SI}}$ from LUX with isospin violation taken into consideration.

In the right panel of Fig. 8, we present IceCube sensitivities to $\sigma_{\chi p}^{\text{SI}}$ with $f_n/f_p \in [-0.8, 1]$ by taking $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ as our input. With isospin symmetry violated, the DM capture rate is suppressed by the factor \bar{F} defined right below Eq. (7). Thus to reach the same detection significance by indirect search, one requires a larger $\sigma_{\chi p}^{\text{SI}}$ to produce enough events. However, isospin violation also weakens the LUX limit at certain range of f_n/f_p . It turns out the sensitivity to $\sigma_{\chi p}^{\text{SI}}$ by IceCube is better than the existing limit by LUX only for f_n/f_p slightly larger or equal to -0.7 . For $f_n/f_p < -0.7$, the LUX limit becomes stringent again while DM capture rate still suffers from suppression from isospin violation.

V. SUMMARY AND CONCLUSION

In this work we have presented the IceCube and KM3NeT sensitivities to thermal-averaged annihilation cross section $\langle\sigma v\rangle$ and DM spin-independent cross section $\sigma_{\chi p}^{\text{SI}}$ for heavy DM ($m_\chi > 10^4 \text{ GeV}$) by detecting DM induced neutrino signature from the Earth's core. To probe the former, we take $\sigma_{\chi p}^{\text{SI}}$ from the LUX bound [31] as the input. To probe the latter, we take $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ as the input. The IceCube sensitivity to $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ in the present case is slightly better than its sensitivity to $\langle\sigma(\chi\chi \rightarrow W^+W^-)v\rangle$ in the case of detecting cosmic neutrino background [35]. On the other hand, the IceCube sensitivity to $\langle\sigma(\chi\chi \rightarrow \tau^+\tau^-)v\rangle$ in the present case is not as good as its sensitivity to $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ in the case of detecting neutrinos from Virgo cluster [38]. Concerning IceCube and KM3NeT sensitivities to $\sigma_{\chi p}^{\text{SI}}$, we have shown that they are roughly one order of magnitude worse than the LUX bound.

We stress that the above comparison is based upon the assumption of isospin symmetry in DM-nucleon couplings. We have shown that, like the direct search, the indirect search is also affected by the isospin violation. The implications of isospin violation to IceCube and KM3NeT observations have been presented in Sec. IV. Taking isospin violation effect into account, the sensitivities of the above neutrino telescopes to both $\langle\sigma v\rangle$ and $\sigma_{\chi p}^{\text{SI}}$ through detecting the signature of DM annihilation in the Earth's core can be significantly improved. As $f_n/f_p \rightarrow -0.7$, the sensitivities to $\langle\sigma v\rangle$ can be better than the natural scale while the sensitivities to $\sigma_{\chi p}^{\text{SI}}$ can be better than the LUX bound.

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- [1] P. Cushman, C. Galbiati, D. N. McKinsey, H. Robertson, T. M. P. Tait, D. Bauer, A. Borgland and B. Cabrera *et al.*, arXiv:1310.8327 [hep-ex].
- [2] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic, , Astropart. Phys. **5**, 81 (1996);Phys. Rev. D **58**, 093009 (1998).
- [3] S. Ritz and D. Seckel, Nucl. Phys. B **304**, 877 (1988).
- [4] F. Halzen and D. Saltzberg, Phys. Rev. Lett. **81**, 4305 (1998).
- [5] S. I. Dutta, M. H. Reno and I. Sarcevic, Phys. Rev. D **62**, 123001 (2000).
- [6] T. K. Gaisser, *Cosmic Rays and Particle Physics* (Cambridge University Press, Cambridge, England, 1992).
- [7] J. F. Beacom, P. Crotty and E. W. Kolb, Phys. Rev. D **66**, 021302 (2002).
- [8] J. Kunnen *et al.* (IceCube Collaboration), Proceedings of the 33rd ICRC, Rio de Janeiro 2013, arXiv:1309.7007 [astro-ph.HE].
- [9] I. F. M. Albuquerque, L. J. Beraldo e Silva and C. Perez de los Heros, Phys. Rev. D **85**, 123539 (2012).
- [10] O. Adriani *et al.* [PAMELA Collaboration], Phys. Rev. Lett. **106**, 201101 (2011).
- [11] M. Ackermann *et al.* [Fermi LAT Collaboration], Phys. Rev. D **82**, 092004 (2010).
- [12] F. -F. Lee, G. -L. Lin and Y. -L. S. Tsai, Phys. Rev. D **89**, 025003 (2014).
- [13] KM3NeT Technical Design Report [ISBN 978-90-6488-033-9];
<http://km3net.org/TDR/TDRKM3NeT.pdf>
- [14] A. Kurylov and M. Kamionkowski, Phys. Rev. D **69**, 063503 (2004)
- [15] J. L. Feng, J. Kumar, D. Marfatia and D. Sanford, Phys. Lett. B **703**, 124 (2011)
- [16] M. Blennow, J. Edsjo and T. Ohlsson, JCAP **0801**, 021 (2008)
- [17] K. A. Olive, M. Srednicki and J. Silk, UMN-TH-584/86.
- [18] M. Srednicki, K. A. Olive and J. Silk, Nucl. Phys. B **279**, 804 (1987).
- [19] A. Gould, Astrophys. J. **321**, 571 (1987).

- [20] L. M. Krauss, M. Srednicki and F. Wilczek, Phys. Rev. D **33**, 2079 (1986).
- [21] M. Nauenberg, Phys. Rev. D **36**, 1080 (1987).
- [22] K. Griest and D. Seckel, Nucl. Phys. B **283**, 681 (1987) [Erratum-ibid. B **296**, 1034 (1988)].
- [23] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, 195 (1996)
- [24] F. Giuliani, Phys. Rev. Lett. **95**, 101301 (2005)
- [25] S. Chang, J. Liu, A. Pierce, N. Weiner and I. Yavin, JCAP **1008**, 018 (2010)
- [26] Y. Gao, J. Kumar and D. Marfatia, Phys. Lett. B **704**, 534 (2011)
- [27] M. G. Aartsen *et al.* [IceCube Collaboration], Science **342**, No. 6161, 1242856 (2013)
- [28] U. F. Katz [KM3NeT Collaboration], Nucl. Instrum. Meth. A **626-627**, S57 (2011).
- [29] M. G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. Lett. **110**, 151105 (2013)
- [30] M. Honda *et al.*, Phys. Rev. D **75**, 043006 (2007)
- [31] D. S. Akerib *et al.* [LUX Collaboration], arXiv:1310.8214 [astro-ph.CO].
- [32] J. F. Beacom, N. F. Bell and G. D. Mack, Phys. Rev. Lett. **99**, 231301 (2007)
- [33] K. Griest and M. Kamionkowski, Phys. Rev. Lett. **64**, 615 (1990).
- [34] L. Hui, Phys. Rev. Lett. **86**, 3467 (2001).
- [35] K. Murase and J. F. Beacom, JCAP **1210**, 043 (2012)
- [36] G. M. Voit, Rev. Mod. Phys. **77** (2005) 207
- [37] A. Diaferio, S. Schindler and K. Dolag, Space Sci. Rev. **134** (2008) 7
- [38] K. Murase and J. F. Beacom, JCAP **1302**, 028 (2013)
- [39] A. Pinzke, C. Pfrommer and L. Bergstrom, Phys. Rev. D **84**, 123509 (2011)
- [40] M. Ackermann *et al.* [Fermi-LAT Collaboration], Astrophys. J. **717**, L71 (2010).
- [41] A. A. Abdo *et al.* [Fermi-LAT Collaboration], Phys. Rev. Lett. **104**, 101101 (2010)
- [42] K. N. Abazajian, S. Blanchet and J. P. Harding, Phys. Rev. D **84**, 103007 (2011)
- [43] B. D. Fields, V. Pavlidou and T. Prodanovic, Astrophys. J. **722**, L199 (2010)
- [44] A. Loeb and E. Waxman, JCAP **0605**, 003 (2006)
- [45] A. A. Abdo *et al.* [Fermi-LAT Collaboration], JCAP **1004**, 014 (2010)
- [46] M. Ackermann *et al.* [Fermi-LAT Collaboration], Astrophys. J. **761**, 91 (2012).
- [47] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **111**, 021301 (2013)
- [48] S. Biagi [KM3NeT Collaboration], J. Phys. Conf. Ser. **375**, 052036 (2012).
- [49] T. R. Slatyer, N. Padmanabhan and D. P. Finkbeiner, Phys. Rev. D **80**, 043526 (2009)